Explanatory report of differentiation of maneuvering coefficients for scaled model vessels

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Introduction

The world is becoming increasingly technically advanced. Cars can drive themselves, factories start to become unmanned, and armies and drones pick their own targets. Not only on a large scale machines are slowly starting to operate themselves, but on smaller scales this occurs more and more. Transport ships across the ocean are quite often computer steered, following a previous calculated path. Even smaller, a towing boat in an international harbour which can moor the bigger vessels safely to the wharf.

In this report we determine and model a maritime vessel in a controlled environment. This report is explanatory, backing the paper "Differentiation of maneuvering coefficients for scaled model vessels". In chapter 1, we find a method on how to calculate and determine a vessel's parameters and use those to dynamically calculate its movement in a controlled environment. Only 3 degrees of freedom will be taken into account. Several forces such as waves, heavy acceleration, water current and wind drag will be neglected due to keeping the model realistically feasible. The result is a strategy on how to implement our model to any given ship and calculate its position in a controlled test environment. This can be achieved when all the necessary parameters are determined using the given experimental strategy, described in chapter 2, and inserted into the obtained model. The model will be explained in chapter 3. After retrieving the data from the experiments, the variables and parameters of the vessel can be translated into a standardized model that will be able to calculate the movement of one specific scaled ship, the Tito Neri. The results of this model will be discussed in chapter 4. Finally, in chapter 5, several conclusions are discussed and future research is recommended.

Literature review

Currently, the theoretical movement of maritime vessels is mathematically thought out. Studybooks (Fossen, 2011) and papers (Pérez & Clemente, 2007) discuss the equations of motion of these vessels. Both are consulted for mathematical purposes in this report. Based on these mathematical equations of motion, there is one model for ships, the Cybership 2 (Skjetne et al., 2004). Several different parameters are essential in modeling a maritime vessel. The paper (Pérez & Clemente, 2007) states a full list of required parameters in the case of modeling a ship and how they influence its maneuverability. Not all of these parameters are needed for this model. In the section "Problem formulation" and "Parametrization experiments" the parameters are defined.

Research question

How can a strategy be developed to make a general model for different purposes, such as model-based maneuvering control and navigation for ships and how to apply this model for the Tito Neri in specific?

With the subquestions:

1. What model should be created to predict the movement of a ship?

There are different kinds of models that can be used to predict the movement of a ship. This sub question determines which of the models will be useful and yet simple enough to describe the general movements of a ship in test conditions.

2. What are the important parameters needed to for this model?

When determined what model to use, there has to be determined what the relevant parameters are in this model.

3. What experiments need to be conducted to find these parameters?

After finding the relevant parameters, one has to think of experiments to determine the said parameters. This is all what the last sub question is about.

Contents

1 Problem formulation

For modeling of maritime vessels, a mathematical basis is needed. The following equation describes the movements of ships (Fossen, 2011)

$$\mathbf{M_{RB}} * \dot{\mathbf{v}} + \mathbf{M_A} * \dot{\mathbf{v}}_\mathbf{r} + \mathbf{C_{RB}}(\mathbf{v}) * \mathbf{v} + \mathbf{C_A}(\mathbf{v_r}) * \mathbf{v_r} + \mathbf{g}(\eta) + \mathbf{g_0} = \tau + \tau_{\mathbf{wind}} + \tau_{\mathbf{wave}} \quad (1)$$

Because a controlled indoor environment was used, without waves and wind and all forces are calculated around the center of gravity of the vessel the equation can be simplified to:

$$\mathbf{M_{RB}} * \dot{\mathbf{v}} + \mathbf{M_A} * \dot{\mathbf{v}} + \mathbf{C_{RB}}(\mathbf{v}) * \mathbf{v} + \mathbf{C_A}(\mathbf{v}) * \mathbf{v} = \tau_{\mathbf{thrust}} + \tau_{\mathbf{drag}} \quad (2)$$

This equation is already simplified for 3 DoF. The sway, surge and yaw are taken into account. It consists of the following parameters:

$\mathbf{M_{RB}}$	=	Mass Matrix
$\mathbf{M_A}$	=	Added Mass Matrix
$\mathbf{C_{RB}}(\mathbf{v})$	=	Coreolis Centripedal Matrix
$\mathbf{C_A}(\mathbf{v})$	=	Added Coreolis Centripedal Matrix
$\tau_{\mathbf{thrust}}$	=	Force Vector of the thrusters
$\tau_{\mathbf{drag}}$	=	Drag Vector of the boat
$\dot{\mathbf{v}}$	=	Acceleration Vector
$\mathbf{v}$	=	Velocity Vector

The model built is a model in 3DoF. The input are the thrust forces of the propellers and the output is a traveled distance in x- and y-direction and the angle the vessel is in. To define the model, equation 2 is rewritten as

$$\dot{\mathbf{v}} = (\mathbf{M_{RB}} + \mathbf{M_A})^{-1}(\tau_{\mathbf{thrust}} + \tau_{\mathbf{drag}} - (\mathbf{C_{RB}}(\mathbf{v}) + \mathbf{C_A}(\mathbf{v}))\mathbf{v}) \quad (3)$$

With of course

$$v = \int \dot{v} dt, \eta = R \int v dt \quad (4)$$

and

$$R = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (5)$$

Using this equations, we can model the acceleration and position by the parameters of the ship.

1.1 Required parameters

For our model, some parameters need to be determined. How these parameters are determined is under the header "Experiments". Here the mathematical properties of these parameters are discussed.

The rigid body mass matrix consists of 2 factors. The mass in the surge and sway directions, and the inertia of the ship around the z-axis. The mass of the ship is measured with load cells. The inertia around the z-axis is determined by experimental approach.

$$\mathbf{M_{RB}} = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I_z \end{bmatrix} \tag{6}$$

For the added mass a similar matrix is used:

$$\mathbf{M_A} = \begin{bmatrix} m_a & 0 & 0 \\ 0 & m_a & 0 \\ 0 & 0 & I_a \end{bmatrix} \tag{7}$$

The Coriolis centripetal matrix can be derived in 6 DoF from the mass matrix (Fossen, 2011) in the following way:

$$\mathbf{C(v)} = \begin{bmatrix} \mathbf{0_{3x3}} & -\mathbf{S}(\mathbf{M_{11}v_1} + \mathbf{M_{12}v_2}) \\ -\mathbf{S}(\mathbf{M_{11}v_1} + \mathbf{M_{12}v_2}) & -\mathbf{S}(\mathbf{M_{21}v_2} + \mathbf{M_{22}v_2}) \end{bmatrix} \tag{8}$$

With

$$\mathbf{M_{CG}} = \begin{bmatrix} \mathbf{M_{11}} & \mathbf{M_{12}} \\ \mathbf{M_{21}} & \mathbf{M_{22}} \end{bmatrix} = \begin{bmatrix} \mathbf{m_{3x3}} & \mathbf{0_{3x3}} \\ \mathbf{0_{3x3}} & \mathbf{I_{3x3}} \end{bmatrix} \tag{9}$$

And

$$\mathbf{S}(\lambda) = \begin{bmatrix} 0 & -\lambda_3 & \lambda_2 \\ \lambda_3 & 0 & -\lambda_1 \\ -\lambda_2 & \lambda_1 & 0 \end{bmatrix}, \lambda = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} \tag{10}$$

This 6x6 matrix can be downgraded to a 3x3 matrix. Only the first and last two rows and columns are used for further computation. This can be done because the other three directions (roll, pitch and movement along the Z-axis) are not taken into account. The actual computation as shown in figure 1 is done by MATLAB, taking the values that are in both red rectangles (vertical and horizontal).

$$
\boldsymbol{C}_A(\boldsymbol{v}) = \begin{bmatrix} 0 & 0 & 0 & 0 & -a_3 & a_2 \\ 0 & 0 & 0 & a_3 & 0 & -a_1 \\ 0 & 0 & 0 & -a_2 & a_1 & 0 \\ 0 & -a_3 & a_2 & 0 & -b_3 & b_2 \\ a_3 & 0 & -a_1 & b_3 & 0 & -b_1 \\ -a_2 & a_1 & 0 & -b_2 & b_1 & 0 \end{bmatrix}
$$

Figure 1: C_A matrix

The τ_{drag} and the τ_{thrust} consist of the following to be determined parameters:

$$
\tau_{thrust} = \begin{bmatrix} F_{thrustx}(n) \\ F_{thrusty}(n) \\ F_{angularthrust}(n) \end{bmatrix} \tag{11}
$$

$$
\tau_{drag} = \begin{bmatrix} F_{dragx}(\theta, v) \\ F_{dragy}(\theta, v) \\ F_{angulardrag}(\omega) \end{bmatrix} \tag{12}
$$

1.2 The used scale model - Tito Neri

To test this model a vessel is needed. We have been provided with a small test vessel from the TU Delft, the Tito Neri. The Tito Neri is a small model tugboat (1:30) of roughly a meter long and width of 30 centimeters. She has two azimuth thrusters on the rear and one bow thruster. This all makes her very maneuverable. The scale model of the Tito Neri is developed to study dynamic behaviour of real ships subjected to autonomous control algorithms. More in depth specifications will be discussed now. A list with specification was provided by the utilisers of the ship. The specifications are the following: The Tito Neri has three 12V DC engines powered by a Pb 12v battery with a 12Ah capacity. The steering is done with two 360 degrees steering propellers which are controlled by a servo motor each. In the front of the boat a basic thruster is mounted (with only 2 thrust directions, +/- 90 degrees). The Tito Neri contains seven sensors: a IMU, GPS, two rpm sensors (propeller rotational speed), a power module for the battery state while charging and a camera. The communication between the computer and the Tito Neri is done with Zigbee protocol based on IEEE 802.15.4 standart in combination with WiFi protocol in a ROS (Robotic Operating System) framework. Also, there's a direct USB link. The hardware consist of: a CPU: 3xARM Cortex-A53, 1.2GHz (Rasberry), MCU: ATMega2560 microcontroller (Arduino Mega). NGCs: a PID controller on the dc motors, a navigation system based on data fusion algorithm algorithm between IMU datas and GPS, dynamic positioning with motion capture camera systems. Again this all is from the specification article provided by the supervisors.

2 Parametrization experiments

Several different parameters are essential in the final model. What these parameters are and how they matter is to be found in the upcoming section. "The influence of some ship parameters on manoeuvrability studied at the design stage" by Francisco Lázaro Pérez and Juan Antonio Clemente (Pérez & Clemente, 2007) state a full list of needed parameters in the case of modeling a ship and how they influence its manoeuvrability. Parameters can be split up into two categories.

1. The first are preset parameters that will be the same no matter the weather condition the ship is in (e.g. length, mass of the ship).

2. The second category consists of time variable parameters (e.g. drift angle, water velocity).

A lot of parameters found in the article can be neglected or left out due to several reasons:

- The fact that we work in only three degrees of freedom (3DoF);

- No rudder present in the current model;

- Neglecting the propeller parameters by reason of its extreme in depth needed knowledge of fluid dynamics and extracting results by experiments instead of calculating.

To be able to model a ship, several leftover parameters from the article stated above are needed to be determined and calculated. The moment of inertia about the z-axis. The x- and y-axis won't be taken into account due to the limited amount of DoF. Also the centre of gravity (CoG), thrust force, drag coefficients (360 degrees), decreasing thrust as a result of acceleration, added inertia and added mass. A series of experiments were designed and executed. These experiments will be listed in a manual. For the below experiments it is necessary to define the body-fixed frame in order to achieve correct data. The x-axis is from the CoG pointing to the bow, the y-axis is pointed from the CoG to the starboard and the z-axis down(for yaw reference).

2.1 Experiments

In this sub section all the conducted experiments will be explained. The experimental data can be found in the dossier that is provided with this report.

2.1.1 Load cells

While conducting most of the experiments, three load cells were used. The particular load cell that was used for these experiments was the 'Load Cell 10Kg-Straight Bar (TAL 220)'.In order to compute the data retrieved from the load cell, an Amplifier is needed between the connection of the load cell and the computer. For this research a 'SparkFun Load Cell Amplifier (HX711)' was used. One for each load cell. For the usage of the load cells in the experiments some alternations were necessary to the load cells. Firstly, the electrical wiring has to be extended. This was done in order to use the load cells in different configurations where the distance to the computer was quite large (around three to four meters). These alternations were done by extending the electrical wires through soldering, see Figure 2. Secondly the load cell amplifiers have to be

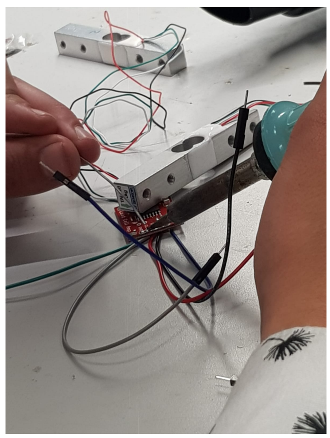

Figure 2: Solding load cell to the amplifier

connected to an Arduino Mega. The University provided one for this research. Finally, to read the data from the Arduino, two code's are required. We will

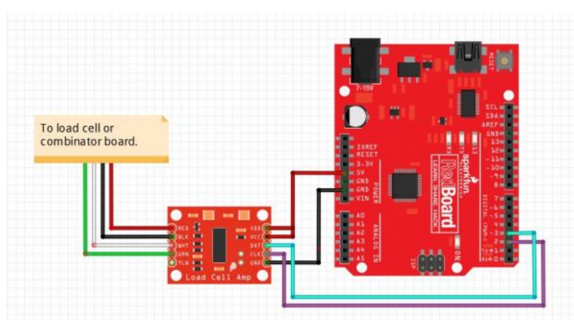

Figure 3: Hookup amplifier to Arduino Mega

call these codes code and code2. The first code is used to calibrate the load cell and is applied to every load cell individually. By hanging known masses on to the frame around the load cell, it is possible to determine the error of the load cell for the given weight and adjust for it. This adjustment factor is called the calibration factor. For every experiment, the load cells need to be recalibrated to make sure the structure around the load cell is not damaged/moved since the last experiment. In the second code, this calibration factor is written into code2. A basic code using one load cell is the base for this code2. Next, code2 is updated and tested for all the three load cells. The code prints the values of all load cells in kg up to a tenth of a gram accurate if the correct calibration factor is filled in correctly. Finally, the load cells are used to determine the force the vessel is subjecting/subjected to. Since it is calibrated for a known set of masses hanged along the z-axis (gravitational direction), a force is acquired if the acquired value in kg, is multiplied by the gravitational acceleration: $9,81 m/s^2$.

2.1.2 Rigid hoop

For most of the experiments a rigid hoop is needed. As seen in section 2.1.6, 2.1.8 and 2.1.7. This section will elaborate on the fabrication of the hoop. See each of the experiments in order to know how the hoop is used. Note that the hoop could be made in many ways. The way how it is done in this research is determined by the available resources at the time. The hoop consist of two rigid aluminum tubes with a diameter of 12mm. Aluminum was chosen to keep the mass as low as possible, while keeping the rigidity. The size of the diameter is chosen because the bending machine has a minimum tube thickness and due to keeping the mass as low as possible, the tube with the lowest diameter was taken. A mould was made to check if the hoop is the correct size, as is seen

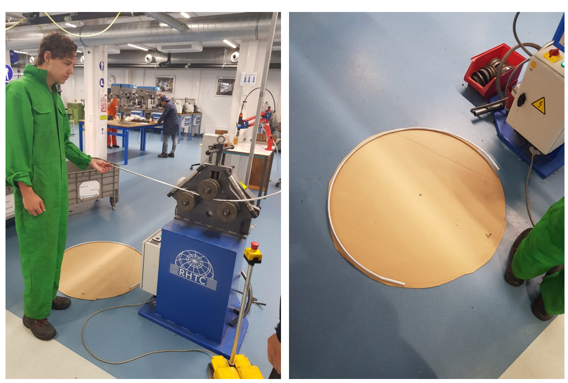

Figure 4: Bending the aluminum tube and mould

in Figure 4. The choice of two aluminum tubes instead of one was because of the limitations of the bending machine. This machine needed 20 cm on each side to get the part in the machine. After the bending all the leftover straight pieces were sawed-off. And the second part of the hoop was trimmed in order to complete the hoop. To attach the two pieces together a welding machine is used. This was provided by the University. The final result is shown in Figure 5.

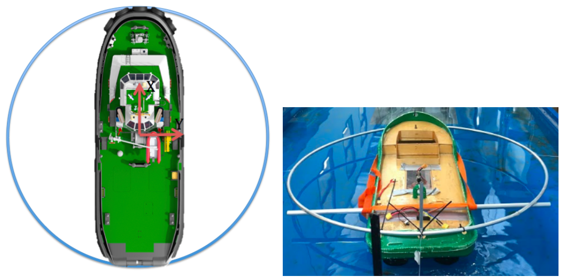

Figure 5: Schematic display on the left real display (Damen, Shipyards, 2018)

2.1.3 Rigid U-frame

The rigid U-frame was specifically made for the moment of inertia experiment, see section 2.1.5. This section will discuss the process of making the frame. Note that the frame could be manufactured in many different ways. The way the frame was made for this research is determined by the available resources at that time. The frame is made by connecting 3 aluminum squared tubes in a U-shape, see Figure 6. Also seen in 6 are the aluminum plates that are 90 degrees on the frame. This is made to increase the surface of contact between the boat and frame. In this way the frame has fewer flex or slide on the boat. Also visible in Figure 6 are the screws to attach the frame to the hooks of the big frame, see (section 2.1.5).

Figure 6: Rigid U-frame

2.1.4 Center of gravity

As is stated before, all experiments will be conducted by having a 3 DoF-system in mind. So for this experiment it is necessary to determine the x-, y- and z-coordinates of the center of gravity as seen in Figure 7. This should be the first experiment to be carried out because the CoG is important for further calculations and experiments. To determine the x-coordinate of the CoG, the boat is secured to two strings, one attached to the bow (front) of the vessel and one attached to its stern (back). The strings are attached to two independent and calibrated load cells (see 2.1.1 for calibration process). Both of the load cells will provide a force. The location of the CoG on the x-axis is then obtained by calculating the momentum about a point such that the sum of the momentum is zero. With the distance known between to two attachment points, these equations will provide the location of the center of gravity on the x-axis.

$$F_1 * L_1 + F_2 * L_2 = 0 \tag{13}$$

Where L_1 and L_2 are defined as the distance of point 1 and point 2 to a point which will be the CoG. The y-coordinate is obtained by making a well considered assumption. The assumption is that the Tito Neri is symmetric about the xz-plane as seen in Figure 7 on the right side. This assumption is in this case made because the left and right of the ship is visibly symmetric. Also the interior of the Tito Neri model is symmetric on it's xz-plane. Thrusters, batteries and other internal hardware is mirrored left and right of the xz-plane. Therefore the assumption that the CoG will be zero in the y-direction and is therefore known. Finally, having the x and y component of the CoG of the vessel, the

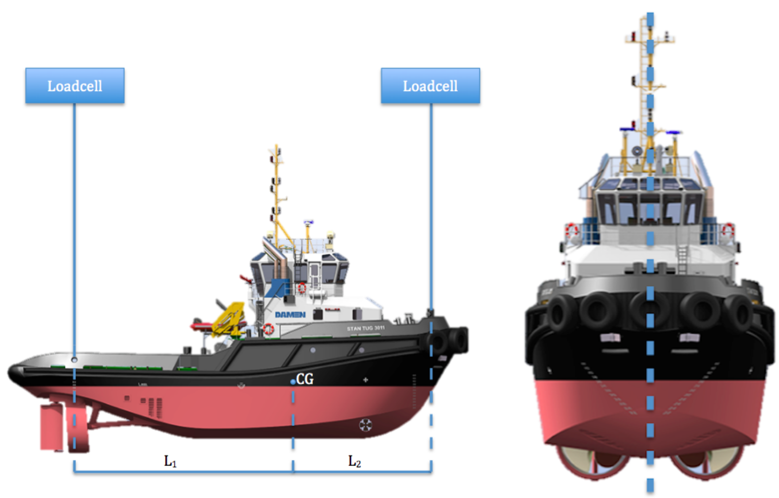

Figure 7: Experimental setting CoG for x and y

only unknown is the height of the CoG, the z-value. To determine the last coordinate, a new experiment has to be conducted. Two rigid beams penetrated with steel rods, will be attached to either side of the vessel as shown in Figure 8. By lifting the ship by two opposed outward pointing rods, one can find the z-coordinate by balance. After lifting the ship will either stay motionless, or it will start to tilt upside down after a slight momentum is applied. If the ship will not tilt and eventually come to a balance in an upright position, one can conclude the z-component of the CoG is above the point of the rod the vessel was lifted with. By moving the two steel rods up or down one can test the location by reaching the tilting point of the Tito Neri. If the ship will tilt, and therefore ends upside down, the CoG is beneath the steel rods. By performing this experiment with a slight change in height of the beams. An assumption can be made in terms of the CoG. If the rods are exactly placed on the z-value of the CoG, the ship can be tilted and will stay in equilibrium for every position.

Figure 8: Experimental setting CoG for the z-coordinate

2.1.5 Moment of inertia

For this experiment keep in mind the research limitation of just 3 DoF. It is sufficient to determine the moment of inertia about the z-axis (yaw). As is stated before, the effects of buoyancy and rolling will be neglected in this research. This experimental setting has been inspired by an experiment that engineers at the NASA's Armstrong Flight Research Center carried out the find the moment of inertia of a plane. (NASA, 2016) The experimental setting consists of two frames. One Large frame which is meant to keep the object in the air. The other frame is constructed in such a way that it will function as the rigid swing between the vessel and the larger frame. See section 2.1.3 for the construction of the frame. Note that it is important for the arm to be rigid otherwise the periodic time will be affected by the arms ability to flex. The goal of this experiment is to acquire the swing time of the vessel in order to calculate its moment of inertia. In this experiment the time the object takes to make a known amount of oscillations will be measured. This will be done by counting the amount of complete swings in a span of time. The data will be computed

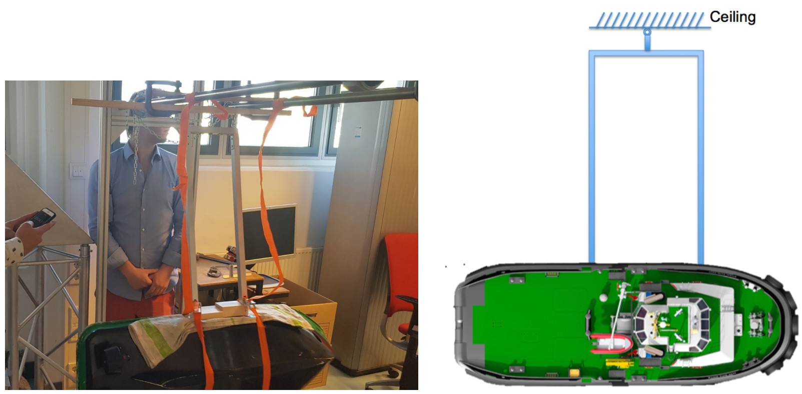

Figure 9: Experimental Setting Moment of Inertia

to acquire the periodic time of the vessel T_com. For the calculation to work the weight of the object and its approximate location of the center of gravity must be known. Using the acquired periodic time we use formula 14 to compute the moment of inertia.

$$I_z = \frac{W_{com} * T_{com}^2 * L_1}{4 * \pi^2} - \frac{W_{frame} * T_{frame}^2 * L_2}{4 * \pi^2} - \frac{W_{vessel} * L_3^2}{Gravity} \tag{14}$$

With:

W_{com}	=	Weight of the vessel and frame combined
W_{frame}	=	Weight of the frame
W_{vessel}	=	Weight of the vessel
T_{com}	=	Oscillation time of vessel and frame
T_{frame}	=	Oscillation time of frame
L_1	=	Length from pivot axis to combined CoG
L_2	=	Length from pivot axis to frame CoG
L_3	=	Length from pivot axis to vessel CoG

2.1.6 Drag (shape)

In order for the model to work the drag-tensor , τ_{drag}, has to be found. The drag of a vessel under a certain angle is the result of its geometric shape of the hull. the drag can be found in many ways. For this research an experiment is chosen that will provide a big set of data in order to compute an overall drag-tensor for the Tito Neri. All the data is stored in Microsoft-Excel. In order to carry out this experiment a rigid hoop, three load cells, an accelerometer and flume tank that enables water-flow in one direction is needed, see Figure 10.

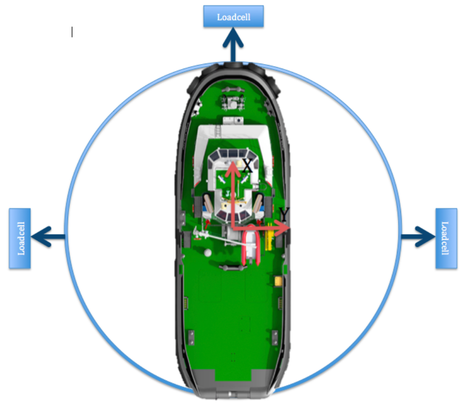

Figure 10: Experimental ring setting

Note that it important that the hoop is rigid. If not rigid, the results will be affected due to the flexibility of the hoop and with the water running, the hoop will oscillate. As is seen in Figure 10 there are three load cells attached to the hoop. The load cells are connected via Arduino to the computer. The data is stored in Microsoft-Excel. As seen in Figure 11, the ship including its ring about its CoG, is in the flume tank. The steel rod emerging from the water contains an accelerometer for accurately measuring the water velocity. The accelerometer is needed because the input of the used flume tank was in percentages, not giving a value for its water velocity.

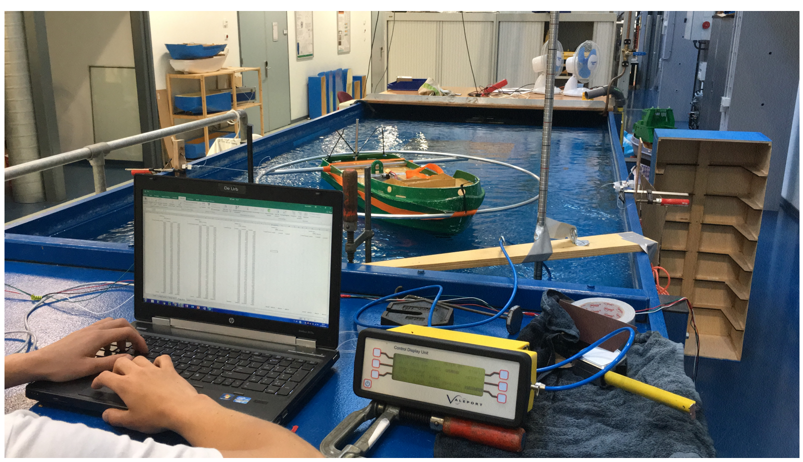

Figure 11: Experimental setting drag

Conducting the experiment the Tito Neri was placed in the water with the bow (front) facing into the incoming water-flow. The calibrated load cells are turned on and are tared. After that the water-flow was turned on and set to the first configuration. This is 5 per cent of the flume's tank velocity capacity. It takes some time before the water reaches a steady velocity. After gaining a constant water velocity and a steady position of ship, measurements during the course of a minute were retrieved and extracted into excel. This data, to be found in the dossier, were averaged out to obtain an average value for the drag of the ship in 5 per cent water flume tank capacity. This exact experiment was also executed at 10, 15, 20 and 25 per cent capacity. The data acquired through the load cells is saved and automatically adopted in an excel file. With completing the experiment for the five different flow velocities, the flume tank is turned off, the Tito Neri will be turned counter clockwise for 10 percent of π and the whole experiment starts over. This is done for all the five different velocities and for all ten angles until the vessel is placed fully backwards. In order to represent the data in a graphical way a MATLAB toolbox, curve fitting, was used. After the assumption that the vessel is symmetric, the retrieved data for one side of the ship can be mirrored for the other side. See section results for more information. A clear representation of the experiment is given for five out of the ten angles in Figure 12. The yaw drag is approximated mathematically,

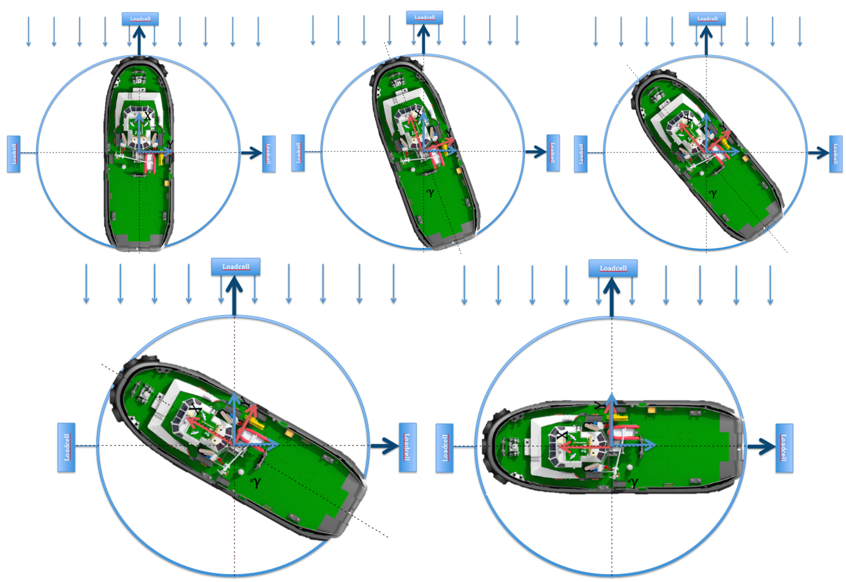

Figure 12: Experiment drag with water flow in five different angles

based on the sway direction of the drag using the following formula:

$$F_{dragangular}(\omega) = F_{dragy}(\frac{1}{2}\pi, R * \omega * \frac{2}{3}) * \frac{1}{3} * l_{ship} \quad (15)$$

$$F_{dragy}(\frac{1}{2}\pi, R * \omega * \frac{2}{3}) \quad (16)$$

This formula is acquired using the free body diagram in Figure 13. The angular

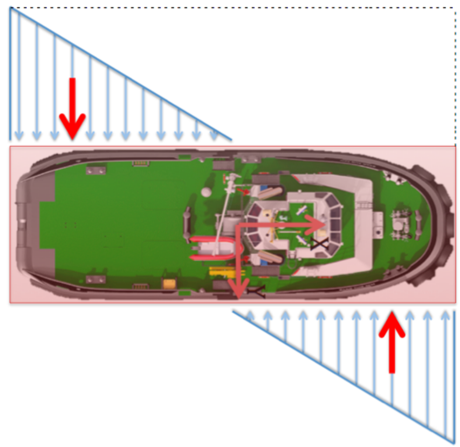

Figure 13: Angular drag force

force is determined based on the drag in the sway direction. Using a linear approximation of the force exerted on the ship by the water in yaw direction, caused by the angular velocity, the total momentum on the ship can be determined. The ship is seen as a solid rectangular block. The working point of the force is placed 2/3 from the middle of the ship. This way the velocity in that point can be determined and put into formula 16 . Using this method, the angular drag is computed using the drag at a 90 degree angle. This is one fourth of the total force in y-direction (see Figure 13).

2.1.7 Thrusters

In this experiment the focus is to obtain the force that the thrusters can deliver together and also separately. The Tito Neri has three thrusters, one bow thruster and two azimuth thrusters in the back as shown in Figure 14.

Figure 14: Location of Thrusters

The Tito Neri is equipped with a bow thruster, but due to the fact of the absence of a sensor, no data can be read. Therefore we disregard the bow thruster in this experiment. For this experiment the rigid hoop from Figure 5 is used and also the load cells. To control the Tito Neri there was a computer with Simulink provided by the University. The objective of this experiment is to attain a big set of data containing the force pulled by the boat with different power inputs. The power input and the speed the propellers of the thrusters is not linear and differ from every thruster. For this reason we chose to compute the force measured by a given RPS (Rounds Per Second) of the motor driving the thruster. Computing the experiment the Tito Neri was placed in the tank and set to a certain input pulling the load cell. The load cell is attached to the stern (back) of the boat in order to collect the pulling force of the boat. This was done for each thruster, using only one thruster at the time, so thruster-specific data is acquired. As in the drag experiments, the thruster is turned on, awaiting the moment the vessel reaches an equilibrium. After that, the data over a period of one minute is retrieved and averaged out. This is conducted for several different increasing inputs, including backward thrust. By finishing the experiment for the first azimuth thruster, the other thruster can be tested. Finally, study the data given if both thrusters are given an input.See results for more information. Note that the flume tank was not given a waterflow.

2.1.8 Added mass

For the model to be successful the added mass is one of the most crucial factors. The added mass of a vessel is the amount of water that is accelerated by the ship as the ship itself is accelerating. Therefore the ship is pushing an added water mass aside. To obtain the added mass the experiments were done in three configurations. The focus of each experiment is to obtain the acceleration in order to calculate the added mass.

2.1.9 Added mass while moving forward

The first experiment has as goal to acquire the added mass of the ship while moving forward in the flume tank. Computing the experiment the Tito Neri is placed in the flume tank with the bow (front) facing into the direction of movement. A set of weights is secured via a string to the Tito Neri. See Figures 15 and 16. Then the weights will be released and they will accelerate the Tito Neri. The time it takes for the weight to fall all the way down to a certain point will be timed. The weight, distance and the amount of time it takes to fall from point 1 to a point 2 is known and can be taken from slow motion video's taken during the experiments to extract the acceleration, initial velocity and final velocity. The added mass will be calculated using the following formula's:

$$m_w * g = m * a + m_w * a + m_a * a + c * V^2 \tag{17}$$

$$m_w * g = m_b * a_b + m_w * a_w + m_A * a_A + F_{dragg}(v_{gem}) \tag{18}$$

Equation 18 will be rewritten to extract the m_A

$$m_A = \frac{m_b * a_b + m_w * a_w + F_{dragg}(v_{gem}) - m_w * g}{a_A} \tag{19}$$

With:

m_w	=	Mass of the weight
m_b	=	Mass of the boat
m_A	=	Added Mass
a	=	acceleration
g	=	gravitational acceleration
$F_{Drag}(v)$	=	Drag function of the Boat
v	=	Velocity

Since $a_b = a_w = a_A$ and a_w is measured with a slow motion camera and $F_{drag}(v)$ and all the masses are known, the added mass in the x-direction can be calculated.

Figure 15: Experiment added mass in x-direction

2.1.10 Added mass 90 degrees shifted

Since the added mass is dependent on the shape of the vessel more experiments have to be carried out. This time the Tito Neri is placed in the flume tank, but rotated by 90 degrees in order to obtain the added mass while moving aside (see Figure 16). Make sure that the vessel has enough distance to travel in order to align itself, otherwise the data will be affected and might not be representative anymore. The added mass is then calculated with formula's 17, 18 and 19.

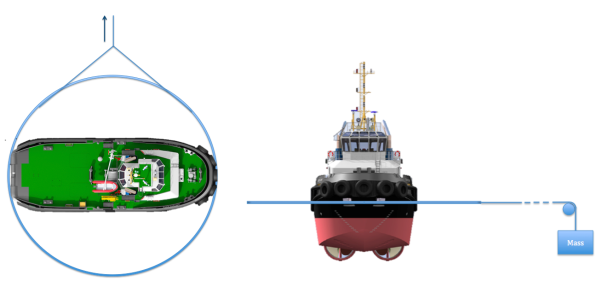

Figure 16: Experiment added mass in y-direction

2.1.11 Added mass while rotating

A vessel of course also has an added mass while surging and swaying. During the yaw of a ship, another added mass is relevant. To gather the data for the added inertial mass, a third experiment had to be executed. The Tito Neri was placed in the water and two identical weights were secured to each side of the bow of the ship via two strings as seen in Figure 17. The ship was winded up to a quarter of the hoop as seen in the first of the two pictures in Figure 17 An identical calculation is then computed to obtain the added mass. What is measured with this experiment is the acceleration of the weights

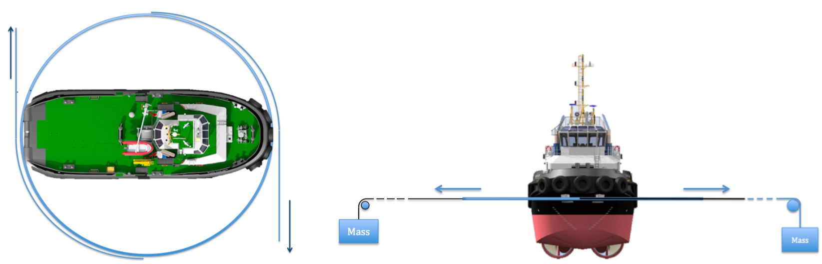

Figure 17: Added inertia experiment top and front view

3 The Simulink model

In this section we will walk trough our Simulink model. The full model can be found in APPENDIX. The model can be divided into three main parts; The thrust , the drag and the mathematical part

3.1 The thrust calculation

In the thrust section the polynomials visible in Figures 18 and 19 is used to calculate the thrust-vector: $\tau_{\mathbf{thrust}}$.

$$\tau_{\mathbf{thrust}} = F_{thrusts}(n_s) * \begin{bmatrix} \cos(\alpha_s) \\ \sin(\alpha_s) \\ \cos(\alpha_s) * y_s - \sin(\alpha_s) * x_s \end{bmatrix} + F_{thrustp}(n_p) * \begin{bmatrix} \cos(\alpha_p) \\ \sin(\alpha_p) \\ \cos(\alpha_p) * y_p - \sin(\alpha_p) * x_p \end{bmatrix} \tag{20}$$

With:

$\tau_{\mathbf{t}}\mathbf{hrust}$	=	Thrustvector
$\mathbf{F_{thrusts}(n)}$	=	Starboard thrust polynomial
$\mathbf{F_{thrustp}(n)}$	=	Port thrust polynomial
$\alpha_{\mathbf{s}}$	=	Starboard azimuth angle
$\alpha_{\mathbf{p}}$	=	Port azimuth angle
$\mathbf{x_s}, \mathbf{y_s}$	=	x and y location of the starboard thruster
$\mathbf{x_p}, \mathbf{y_p}$	=	x and y location of the port thruster

3.2 The drag calculation

The calculation of the drag is a bit more complicated than the calculation of the thrust. Whereas the basic principle is the same, processing in a polynomial function, it is way more complicated for the drag polynomial. This has two reasons; The first reason is that the drag is a two variable polynomial, the second reason is that the variables needed are difficult to extract from the velocity vector ν. As visible in Figure 20, the drag in the x and y are dependent on the velocity in the x or y direction and the angle between the velocity vector and the x-axis of the vessel. So the $\tau_{\mathbf{Drag}}$ is calculated in Simulink in the following three steps:

3.2.1 Step 1: The extraction of the angle and velocity

At first the first two elements of the vector ν are used to determine the angle between the velocity vector and the x-axis of the vessel. This is done in the angle function block in Simulink. The output of this block is a vector, $\begin{bmatrix} Angle & \nu \end{bmatrix}$. With the v being the velocity in the x or y direction. The angle is always declared positive, this is so it can correctly be inserted in our polynomial function.

3.2.2 Step 2: The polynomial function

To use the polynomial function determined in the drag experiment, an extra MATLAB box is required . This is because Simulink does not support the fit function of the MATLAB toolbox for 3D meshes. The fit is therefore obtained with the use of an interpreted MATLAB function. To use this function, the fit first has to be declared a separate function. This is done by running the .m file 'parameters.m' After declaring the function, it is possible to 'call' the function with the previously determined vector.

3.2.3 Step 3: The direction of the drag

Now the absolute drag is obtained. The direction is, at the moment, always positive. Given that the drag always has to counteract the direction of the velocity, an if function was used. It states that if the velocity is positive, the drag should be multiplied by -1.

Putting these three steps together the drag vector, τ_{drag}, can be calculated.

3.3 The mathematical part

The mathematical part of the model is based on the '3DoF Equations of motion' block from the MSS GNC toolbox made by Fossen (Fossen, 2011). It basically describes the formulas 3 and 4 in one Simulink block.

When combined the drag, thrust and math complete the Simulink maneuvering model of the vessel.

4 Experiment results

The final goal of the research is to achieve a strategy and successfully implement the model to the Tito Neri. During the research, results of the experiments must be registered and executed thoughtfully specify the estimated trajectory as well defined as possible. Using the experiments precise data was gathered and verified in virtue of the given equations of motion stated by (Fossen, 2011). By measuring the dragcoefficient in every degree around the tested vessel, the hull coefficient can be plotted and fitted to obtain a clear view of the ships drag forces. Looking at the results, a quadratic relation can be seen between the dragforce and velocity of the water. Combined with the fact that the ship will have an increase in dragforce the more it is positioned sideways as seen Figures 20 and 21. The added mass differs around the ship, as we found in our experiments. The added mass of the ship if facing forward was about 30 per cent of the ships weight, while the 90 degree rotated ship had an added mass of around 300 per cent. A ships hull is designed to generate a low as possible added mass in the sailing direction the interest of minimising the dragforce. Experiments confirm this. Finally, performing the experiments, collect and extract the parameters appropriately, these can be substituted to the overall model and show that the model can estimate and determine the position of the ship within the boundaries of error. In Figure 22 all the determined parameters due to the experiments are portrayed.

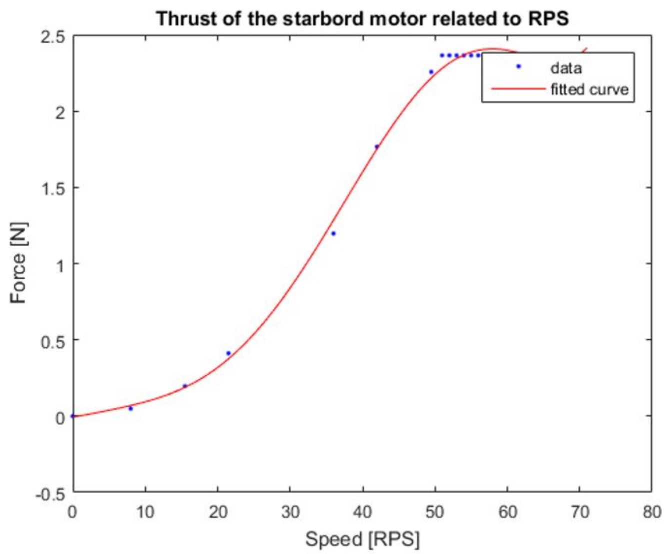

Figure 18: Results thrust

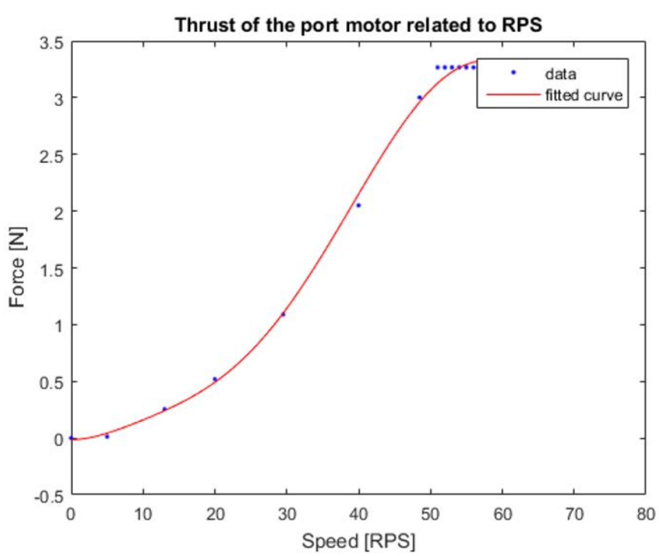

Figure 19: Results thrust

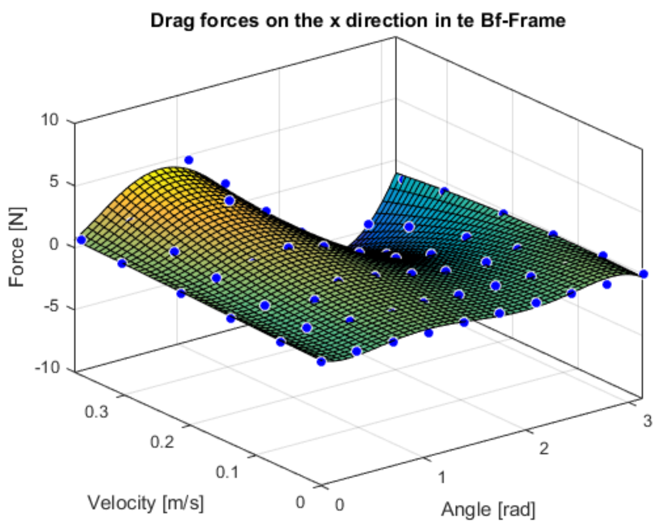

Figure 20: Results drag

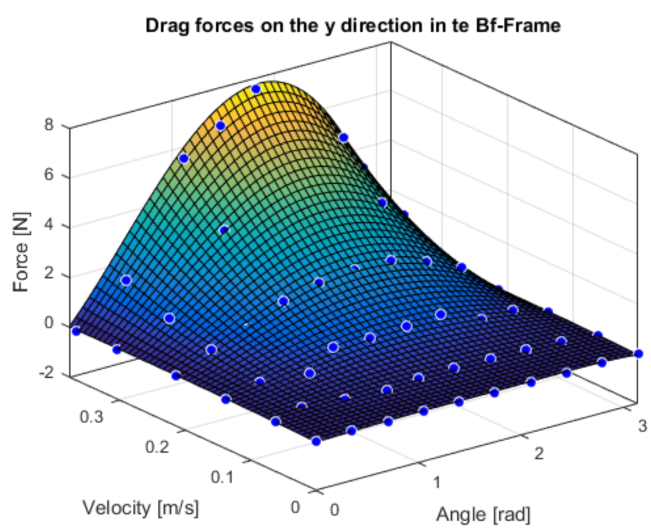

Figure 21: Results drag

Parameter	Symbol	Value	Unit
Mass of the ship	m_b	16.9	kg
Mass matrix	M_{RB}	$\begin{bmatrix} 16.9 & 0 & 0 \\ 0 & 16.9 & 0 \\ 0 & 0 & 0.51 \end{bmatrix}$	$\begin{bmatrix} kg \\ kg \\ kg * m^2 \end{bmatrix}$
Added mass matrix	M_A	$\begin{bmatrix} 1.2 & 0 & 0 \\ 0 & 49.2 & 0 \\ 0 & 0 & 1.8 \end{bmatrix}$	$\begin{bmatrix} kg \\ kg \\ kg * m^2 \end{bmatrix}$
Length ship	l	0.97	m
Width ship	w	0.3	m
Center of gravity	CoG	$\begin{bmatrix} 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} m \\ m \end{bmatrix}$
Port-thruster location	-	$\begin{bmatrix} -0.42 \\ -0.08 \end{bmatrix}$	m
Starboard-thruster location	-	$\begin{bmatrix} -0.42 \\ 0.08 \end{bmatrix}$	m

Figure 22: Parameters Tito Neri

4.1 Validation

After experimenting and making a model in Simulink, tests have to be performed for validation.The Simulink model has to accord to real sailing tests. If the model and tests correspond up to a certain level, the parameters found were successfully modeled.

4.1.1 Thrustvector (with current)

As is stated before the experiment with the thrusters had as goal to obtain the amount of force the thrusters can deliver (2.1.7). This experiment has as goal to find out what force input is needed when there is a current flowing towards to bow of the boat. This has to be done for validation purposes. For this experiment just the tank and the computer with Simulink were used. The flume tank was set to a configuration of a set of different current speeds. With every speed of the current the Tito Neri was placed into the water and controlled to obtain a speed such that the vessel is not pushed back by the current but also will not move into the current. We retrieved the powerinput from Simulink. The outcome were in line of our model, shown below.

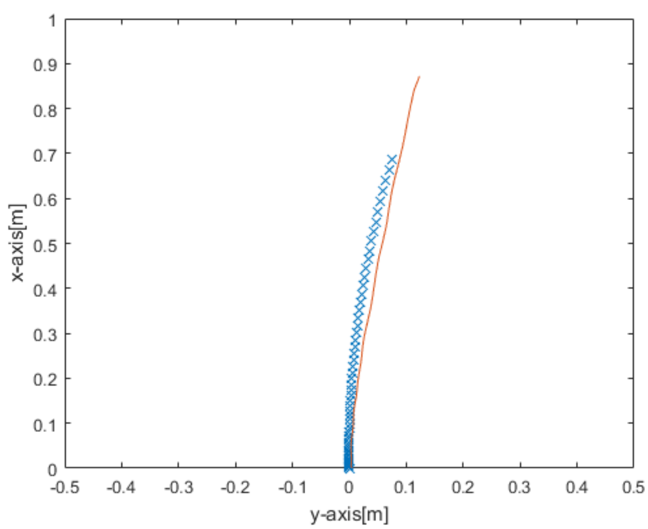

Figure 23: Simulation results

4.1.2 Center of gravity

The center of gravity was validated by simply balancing the vessel on a rod in the x-axis. This verified the center of gravity on that axis. The same verification was done for the y-axis.

4.1.3 The Simulink model

To verify the model, the traveled path was observed with a camera, see Figure 24. The cross line is the traveled distance according to the model, while the straight line is the path traveled according to the camera (with a +/- 2 cm accuracy). The accuracy of the model in comparison with the path observed by the camera, is up to 93 per cent in the x-direction and 90 per cent in the y-direction. However also visible in Figure 24, the accuracy differs a lot. This is largely due to the starting position of the ship being not perfectly zero. If the ship starts with a small angle, the distance traveled in y direction will be greater than the direction it would have traveled without the angle. Also, two different computers were used, one to run the model and one to run the camera. The simulation time is therefor not equal, making the results less comparable.

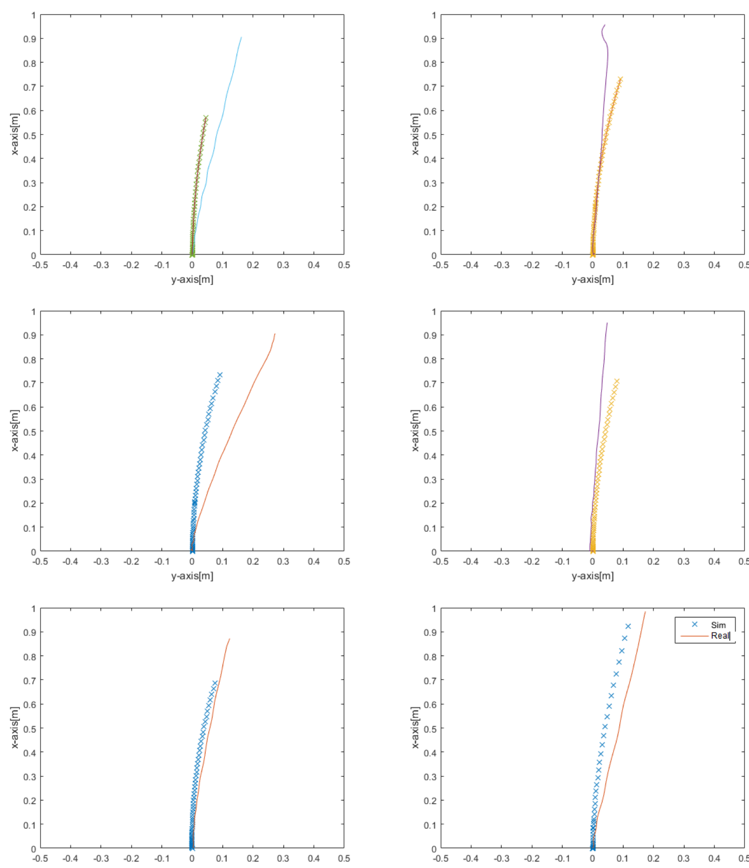

Figure 24: Simulation results

5 Conclusion

In this section the conclusion of our experimental parameter determination and model will be drawn. Furthermore, suggestions for future research will be given.

In this report the method to model a maritime vessel is determined. Regarding the parameters that are to be determined to model a maritime vessel , five different experiments were conducted: Thrust [N], added mass [kg], drag vectors [N], inertia [kg*s^2] and the CoG [0,0,0]. The drag experiment is developed for this paper and two meshes were created for the surge and sway drag. The yaw drag is calculated based on the drag in the sway direction. The thrust experiment was conducted the same way as the drag experiment, but with throttle from the Tito Neri. Using these parameters in the model, the predicted path was plotted in Simulink. Using a camera hanging above the testing facility and three LEDs on top of the ship, the position of the ship was tracked. These measurements were compared to the results of the created model, see Figure 23. The results proved the model is a basis for control of maritime vessels. With surge and sway respectively averagely 90 and 85 per cent accurate, an estimation of the location of the ship can be determined. For future research, our main recommendation is that this model is linked to controllers adjusting for deviations. The same applies for path planning. Furthermore, improvement recommendations are suggested in the next section.

5.1 Discussion

The University provided the flume tank for this research. Due to the shallow waters in the tank, added mass and thrusterforce are influenced. Because the model is verified in this tank, it does not matter. But in future research, water depth of the tank has to be taken into account for accurate results. If the vessel is tested in 2 different tanks it can lead to scale problems. There are more points to be taken into account about the research facilities: the input for the water velocity in the water tank is in percentage. So if a current is used in an experiment the water velocity should be measured with an acceloremeter. This has to be done because the flume tank is not precise enough to give a given speed at a certain percentage. The speed varies each time the flume tank is utilized again. Next up is the liability of equation 14. The NASA formula is, since it is developed by NASA, reliable. Yet since it is modulated in imperial units, it has to be rewritten for SI units. The measurement method of the moment of inertia experiment can be improved. A stopwatch was used to determine the oscillation time. Even though 10 periods were timed, there is still a human error because the human reaction time is around 0.3 seconds. Furthermore, friction, air and friction of the setup, is not taken into account in this formula. The moment of inertia around the x-axis and y-axis don't have to be calculated in a 3DoF model, since none of the mathematical equations have need for these parameters. If the model is to be expanded to 6DoF however, the inertia around the x- and y-axis are to be determined to complete the (added)mass matrix.

The total thrustforce is calculated based on the force excerted on the water by the propulsion system. The weight of the hoop is not of importance here, only the (force)output is measured. The weight of the hoop is, however, important for the added mass because the ship will be heavier to begin with. As is stated in section 2.1.7 the bow-thruster is not taken into account because of the lack of a rps-sensor. For future research one could construct a motor with a rps-sensor so that all the vessel's thrusters can be taken into account. load cells: The setup of the load cells has been explained in section 2.1.1.Note that in every experiment the calibration of the load cells has to be checked. In the case of this research every time an experiment had to be carried out the load cells were calibrated again for changes in output due to movement and adjustment. Hoop: The hoop has to be rigid otherwise some of the data could be affected and not representative any more. If the hoop isn't rigid there will be oscillations due to the flexibility of the hoop. The vessel will participate in these oscillations.The rigid hoop is self-made so it is possible that it is not perfectly round due to the heat production in the welding process. The bending was done by laying the hoop on a mould, see section 2.1.2. This was done by eye and therefore a human error factor is introduced that could cause the hoop for not being 100 per cent round. Several experiments were executed using stopwatches which are manually started and stopped. This might give a measurement error and therefore results may not be as accurate as expected. In the experiments the following factors were neglected:

- The friction in the pulleys;
- The strain in the used cables;
- Strain in the hoop;
- Difference in viscosity of the water during different surrounding conditions;
- Air friction.

5.2 Further research

We recommend the next followup experiments and improvements to optimize the model; The added mass is calculated correctly, but with basic equipment. Use of more advanced camera's, accelerometers and longer flume tank can improve the results of the experiment. For drag, a calculation based on the sway drag is used to determine the yaw drag. An experiment developed specifically for the yaw drag would be more accurate. Furthermore, wind and wave drag are neglected. To improve the model and test it in an outside environment, these should be taken into account. We also recommend to design new thrusters for the Tito Neri. The thrusters are currently made of plastic and the starting angle is close to 0, but not exactly. Using rigid thrusters that don't deform and start in the exact 0 degree position, more precise testing of the model can be conducted. We also recommend a more accurate camera and a larger flume tank to verify the model. The range of the camera is limited and it's inaccuracy is +/- 0.02 meters. With deviations of only 5 centimeters in y direction in some of the test, this error is over 50 per cent. Two computers were used, one to run the model and one to run the camera. The simulation time is therefor not equal, making the results less comparable. Finally, the starting position of the ship was not perfectly zero. If the ship starts with a small angle, the distance traveled in y direction will be greater than the direction it would have traveled without the angle. The general conclusion of these difficulties is that an improved verification setup is required for future testing.

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